SPECTROPHOTOMETRIC PECULIARITIES OF SOME SATELLITES OF PLANETS

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ABSTRACT: Stebbin's and Jacobsen's photoelectric measurements of the solar phase-brightness relationship for Jupiter's Galilean satellites are used to show that the surface layers of the satellites are very porous. The parameter g that characterized relative density of a surface layer is equal to 0.2 for Callisto. Results of spectrophotometric observations of satellites are discussed briefly from the point of view of the possible nature of their surfaces.

Photometric observations of satellites of planets, as a class of objects /49 devoid of atmosphere (with certain exceptions), can be quite adequately used to arrive at a judgment as to the microrelief of the upper layer of their surfaces, and in part, as to the nature of the surface layer itself. In any case, as the long years of experience gained from photometric study of the Moon have shown, data from photometric observations, such as the brightness-phase angle relationship, the spectral variation in the albedo, disk brightness distribution, and other features, had led to rather definite conclusion as to the microrelief of the lunar surface and had made it possible to arrive at certain judgments as to the nature of the material of which the lunar surface layer was comprised.

Unfortunately, as distinguished from the Moon, photometric data on satellites of planets is quite limited because of the small angular sizes of these bodies and the limitations on the phase angles at which they can be observed from the Earth. Moreover, the accuracy of photometric observations is greatly reduced in many cases because the satellites are relatively dim, and are quite close to the central body.

Still, photometric (using light filters) and spectrophotometric observations are a quite effective means for studying this group of objects.

The Brightness-Phase Angle Relationship for the Galilean Satellites of Jupiter

In 1926, Stebbins [1], and in 1927, Stebbins and Jacobsen [2], collected numerous photoelectric measurements of the brightness of the bright satellites of Jupiter for a whole set of observed phase angles (up to 11°). The principal

goal of these observations was to study variations in the brightness of the satellites with phase rotation around a central body. The data obtained are close to B in the color system and unquestionably indicate the variation in the brightness of all four satellites with phase rotation.

The data compiled by Stebbins and Jacobsen have been discussed over and over again, and when these data were supplemented by those obtained in the 1950's at the McDonald Observatory it became conclusive there is a longitudinal effect in the brightness, and sometimes in the color, of the Galilean satellites. The latter evidently is associated with the mottled structure of their surfaces. Callisto is distinguished by maximum changes in brightness with phase rotation when the solar phase angles are large.

Let us pause briefly to consider the results of the observations obtained by Stebbins and Jacobsen as they pertain to the relationship between the brightness of the satellites and the solar phase angle.

Figure 1 shows the brightness of the satellites in terms of phase angle from 20-30 measurements that more or less uniformly cover the phase angles between 0.3° and 11°. The curves approximate well a square-law function of the following type in the case of linear extrapolation of the measurements for the zero phase shown in Figure 1

$$m = m_0 + a\alpha + b\alpha^2$$

when constants a and b have the following values

Jupiter I (Io)	a = 0.046;	b = 0.001;
II (Europa)	0.0312;	0.00125;
III (Ganymede)	0.323;	0.00066;
I (Callisto)	0.090;	0.036.

Callisto's phase function is equated to the wing side of the satellite (the darker side near the opposition). For the leading side

$$m = m_0 + 0.112 + 0.060\alpha - 0.0019\alpha^2.$$

The curve for the lead side in Figure 1 is designated IV.

As will be seen from Figure 1, Callisto's lead side is distinguished by maximum increase in brightness toward the opposition. The brightness differential for the extreme values of α (upon extrapolation of the measurements for α = 0 according to Stebbins and Jacobsen) is $0^m.55$. A more careful consideration

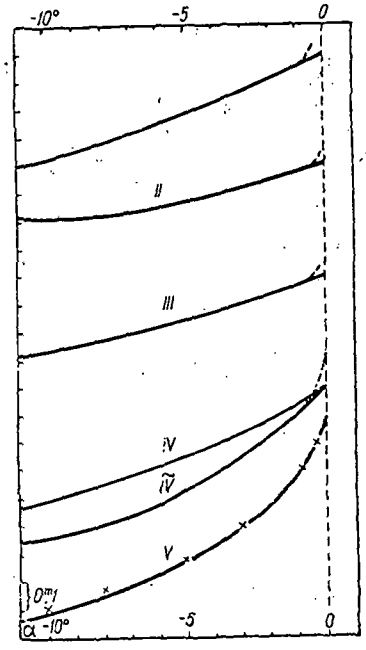

Figure 1. Phase-brightness relationship. I- Io, II- Europa, III- Ganymede, IV- lead and V- wing sides of Callisto. x- asteroid 20 Massalia. x-axis- phase angles; y-axis- brightness, in stellar magnitudes.

of the Stebbins and Jacobsen measurements shows a tendency toward a sharp rise in brightness for all four satellites between 1° and 0° (the broken lines in Figure 1). This effect is particularly well defined in the case of Callisto (lead side) where there are four measurements in the interval of phase angles noted.

So the greater probability is that the actual brightness differential for the satellites should exceed the value taken directly from the Stebbins and Jacobsen phase curves for phase angles between 0° and 11° (Figure 1, solid curves).

The magnitude of the effect of opposition between 1° and 0° can be evaluated for Callisto by using the results obtained by Stebbins and Jacobsen and the procedure detailed in reference [3].

This satellite's geometric albedo is comparatively low ($P(B) \approx 0.2$). We can, therefore, as in the case of the moon, disregard the effects of higher order scattering and make full use of the calculations given in reference [3]. We can, in particular, determine the parameter g, characterizing the relative density of Callisto's surface layer. To do so, let us use the data listed in Table 1 for the planet's phase-brightness relationship for different g values, according to reference [3]. By using the phase-brightness relationship for Callisto between 1° and 11° we obtain $g \simeq 0.2$ for the satellite's lead side (see Figure 1, IV). According to reference [3], $g = 0.25$ for the lunar surface layer (see Figure 1, V). The increase in Callisto's brightness (lead side) is $0^m.28$ between 0° and 1° for the g value found, and the brightness differential for the interval between 0° and 11° is about $0^m.75$.

This conclusion as to the structure of the surface layer on Callisto's lead side is valid only if this layer satisfies the Hapke model, of course [4].

T. Gehrels, in 1955, took photoelectric measurements of the phase-brightness relationship for the asteroid 20 Massalia [5]. Table 2 lists the color characteristics of this asteroid, and Figure 1 shows its phase function in the V system (crosses), which is virtually no different from the lunar phase function or that of Callisto's lead side. /51

TABLE 1. PHASE-BRIGHTNESS RELATIONSHIP FOR A PLANET NEAR OPPOSITION FOR DIFFERENT VALUES OF THE PARAMETER g

α	g					
	0.05	0.1	0.2	0.3	0.4	0.5
0°	0^m00	0^m00	0^m00	0^m00	0^m00	0^m00
1	0.62	0.47	0.28	0.18	0.14	0.11
2	0.68	0.58	0.41	0.30	0.23	0.17
3	0.71	0.63	0.49	0.38	0.30	0.24
4	0.72	0.66	0.54	0.40	0.35	0.29
5	0.73	0.68	0.57	0.48	0.40	0.34
10	0.76	0.74	0.67	0.61	0.59	0.48
15	0.80	0.78	0.73	0.68	0.63	0.58

TABLE 2. SOME CHARACTERISTICS OF PLANETARY SATELLITES

Planet and its satellite	Radius, km	Mean density, g/cm³	Absolute stellar magnitude (V)	$m_{sat} - m_\odot$					A_g (V)
				U	B	V	R	I	
Jupiter									
I - Io	1660	3.9	—1.90	1.70	0.54	0.00	—0.21	—0.24	0.92
II- Europa	1440	4.0	—1.53	0.62	0.24	0.00	—0.12	—0.14	0.83
III- Ganymede	2470	2.5	—2.16	0.56	0.20	0.00	—0.14	—0.16	0.49
IV- Callisto	2340	1.7	—1.20	0.64	0.23	0.00	—0.16	—0.19	0.26
Saturn									
Enceladus	300	0.6	2.22	—	0.01	0.00	—	—	0.54
Tethys	600	0.7	0.72	0.35	0.15	0.00	—	—	0.84
Dione	650	0.85	0.89	0.24	0.08	0.00	—0.03	—0.06	0.94
Rhea	900	0.75	0.21	0.34	0.13	0.00	—0.16	—0.13	0.82
Titan	2500	2.7	—1.16	1.28	0.67	0.00	—0.43	—0.25	0.21
Hyperion	200	3.3	4.61	0.34	0.06	0.00	—	—	—
Iapetus	600	5.5	1.48	0.49	0.08	0.00	—	—	—
Uranus									
Titania	500	—	1.30	0.10	—0.01	0.00	—0.07	—0.19	—
Oberon	400	—	1.49	0.12	0.02	0.00	—0.04	—0.08	—
Neptune									
Triton	2000	4.6	—1.16	0.40	0.14	0.00	—0.13	—0.28	0.36
Nereid	150	3.6	4.00	—	0.17	0.00	—	—	—
Luna	1738	3.34	0.21	0.61	0.29	0.00	—0.35	—0.52	0.11
20	—	—	6.77	0.47	0.19	0.00	—	—	—

The wing side of Callisto is less porous, so the effect of opposition is not as sharply defined. We obtain g = 0.6 directly from curve IV in Figure 1, and by using Table 1. If it is taken that the albedo of the satellite's surface on the wing side is approximately 10 percent less than on the lead side, g = 0.5, roughly, for the wing side, and this is approximately the porosity of the "average Mars" [6].

The high albedo of the first three Galilean satellites is such that it is /52
not as simple to determine g (as in the manner of the foregoing) and this is so because higher order scatterings must be included. But given the same surface layer porosity, there should be a decrease in the magnitude of the observed effect of opposition with increase in surface albedo [7]. If, for example, we take the case of the very high albedo of Io (the geometric albedo in the B system is about 0.6) we find that the satellite's phase curve still shows a brightness differential of about $0^m.4$ between 0° and 11°, and this means its surface porosity also is quite high. This is true to the same degree for the satellites Europa and Ganymede. Overall, this result is in good concordance with Ganymede's low thermal inertia, found by measuring the thermal radiation when the satellite enters Jupiter's shadow [8].

The conclusion as to the high degree of porosity of the surface layers of the Galilean satellites of Jupiter must be considered when analyzing spectrophotometric observations in order to study the nature of the upper covers of satellites.

Albedo and Spectral Energy Distribution for Satellites

Today we put the relationship between the albedo of the Galilean satellites of Jupiter and the wavelength at 0.35-2.5 microns. Photoelectric measurements with light filters [9] are quire reliable in the 0.35-0.82 region. Spectrophotometric data in the visible [10] and IR regions [11] of the spectrum are fragmentary and are in need of refinement. The geometric albedo of the first two satellites in the red region of the spectrum is puzzlingly high (Table 2).

The geometric albedo, p, the apparent albedo in the center of the full disk, ρ, and the smoothness factor for the surface, q, for a planet devoid of atmosphere are linked by the relationship [12]

$$p = \frac{2}{q+2}\rho.$$

Customarily $\rho > p$, but $q \simeq 0$ and $\rho \simeq p$ for Callisto, at least in the short-wavelength region of the spectrum (where the satellite's geometric albedo is approximately that of the Moon's). q increases with increase in the albedo [7, 13], so the differential in the apparent albedo between 0.35 and 0.82 microns should be even greater than that in Table 2 for the geometric albedo differential, and this would apply to all the Galilean satellites, particularly Io.

Attention is drawn to the fact that the high value of the satellite's albedo corresponds to its high mean density (Table 2). The conclusion that suggests itself is that the diameters of Io and Europa are greatly in error as determined (understated) and this is particularly so if it is considered that the angular diameters of these satellites are comparatively small and they are closer to Jupiter than are Ganymede and Callisto, making precise micrometric measurements against Jupiter's background difficult.

Camichel [14] and Dollfus [15] have obtained Io and Europa diameters that are somewhat larger than those accepted earlier, but the corresponding corrections do not change the main point; the albedoes of Io and Europa still are very high.

A high albedo has been determined for Saturn's satellites Tethys, Dione, and Rhea, but these data cannot be trusted because the diameters of these distant satellites cannot be measured directly from the earth. Perhaps the only reliable photometric characteristics of all planetary satellites, with the exception of the moon and the Galilean satellites of Jupiter, are their brightness and spectral energy distribution. /53

V. I. Moroz [16] measured the IR spectrum of the Galilean satellites of Jupiter at 0.7-2.5 microns and has suggested that at the very least much of the surface of Europa and Ganymede can be covered by ice. However, according to reference [17], ice has an inverse albedo behavior with respect to the spectrum as compared to that found by observation. If one attempts to explain the comparatively small drop in energy toward the violet end of the spectrum for Europa by the presence of hoarfrost through which the satellite's own surface is translucent, there is still no way to explain the data for Io. The question of the presence of an atmosphere for the Galilean satellites still is an open one.

The 2-meter reflector at the Shemakha Astrophysical Observatory was used during 1968-1969 by Yu. D. Davudov to obtain some 60 spectrograms of the Galilean satellites of Jupiter and of Titan in the 0.40-0.65 micron band. The observations were made in the Cassegrain focus using a diffraction spectrograph (dispersions 30 and 75 Å/mm). The comparison stars were selected from the Kharitonov catalog [18], and G. F. Sitnik's data [19] were used to effect the photometric tie between the satellite spectrograms and the sun. Mean curves of spectral energy distribution in the spectra of Io (16 spectrograms), Europa (9), Ganymede (7), Callisto (7), and Titan (17), are shown in Figure 2. They are in satisfactory agreement with data by other authors if consideration is given to the fact that the color index for the satellites undergoes change with phase rotation.

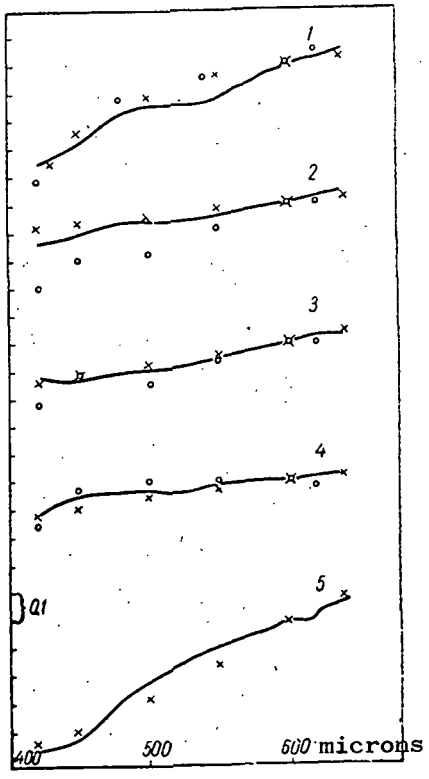

Figure 2. Relative spectral energy distribution. 1- Io; 2- Europa; 3- Ganymede; 4- Callisto; 5- Titan. x- Harris' measurements; o- Priboyeva's measurements; y-axis- logarithms of intensity.

The satellite spectrograms were compared with the lunar spectrum in the region of the 6190 Å CH_4 band. This band is well separated in the Titan spectrum. Its equivalent width is about 20 Å [20]. Careful measurements of the spectrograms for Jupiter's satellites showed no traces of the 6190 Å CH_4 band noted earlier by other observers. We can add to this the fact that the spectral behavior of the Io albedo is, in general, quite difficult to explain by the influence of the atmosphere. If one assumes the satellite to have a neutral surface with a high albedo in this region of the spectrum, it would be necessary to have an atmosphere with a quite complex optical modulus in order to have satisfactory observations. This atmosphere would have to have a relatively great optical thickness and significant true absorption over the whole of the 0.35-0.82 micron band, and this is hard to square with the high albedo of the satellite in the red rays.

Io's color changes greatly with phase rotation, reaching a value of about $0^m.65$ in the U-V ($\simeq 0^m.2$ in B-V and $\simeq 0^m.45$ in U-B). This means that the magnitude of the longitudinal effect on Io's brightness increases from V to U. In other words, the contrast between the dark formations on the satellite's surface and their surroundings increases toward the violet end of the spectrum. So far as /54 the other three Galilean satellites are concerned, the contrast in details in the U, B, and V is almost the same [9]. This effect, which can be observed for Io, could be imparted by an atmosphere in which the true absorption dominates the scattering, and the optical thickness increases toward the violet end of the spectrum. Then it would have to be assumed that there are areas of relief with reduced levels in the longitude region near 300° (corresponding to the minimum brightness of Io near opposition). But the lack of observed atmospheric criteria for Io detracts from the validity of this hypothesis.

Evidently the entire surface is primarily responsible for the observed behavior of spectral values for Io, and this would apply to the overwhelming majority of other planetary satellites as well, although neither asteroids nor meteorites have albedo spectral values similar to those for this satellite [17]. On the other hand, there still is not sufficient grounds for the final rejection of the atmosphere hypothesis. In any case, the comparatively small mass of the Galilean satellites, and the absence in their spectra of CH_4 molecular bands, still is not the deciding argument in favor of this rejection.

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